2 TEMPERATURE-RELATED DEATH AND ILLNESS

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2 TEMPERATURE-RELATED DEATH AND ILLNESS

Key Findings

Future Increases in Temperature-Related Deaths

Key Finding 1: Based on present-day sensitivity to heat, an increase of thousands to tens of thousands of premature heat-related deaths in the summer *[Very Likely, High Confidence]* and a decrease of premature cold-related deaths in the winter *[Very Likely, Medium Confidence]* are projected each year as a result of climate change by the end of the century. Future adaptation will very likely reduce these impacts (see Changing Tolerance to Extreme Heat Finding). The reduction in cold-related deaths is projected to be smaller than the increase in heat-related deaths in most regions *[Likely, Medium Confidence]*.

Even Small Differences from Seasonal Average Temperatures Result in Illness and Death

Key Finding 2: Days that are hotter than usual in the summer or colder than usual in the winter are both associated with increased illness and death *[Very High Confidence]*. Mortality effects are observed even for small differences from seasonal average temperatures *[High Confidence]*. Because small temperature differences occur much more frequently than large temperature differences, not accounting for the effect of these small differences would lead to underestimating the future impact of climate change *[Likely, High Confidence]*.

Changing Tolerance to Extreme Heat

Key Finding 3: An increase in population tolerance to extreme heat has been observed over time *[Very High Confidence]*. Changes in this tolerance have been associated with increased use of air conditioning, improved social responses, and/or physiological acclimatization, among other factors *[Medium Confidence]*. Expected future increases in this tolerance will reduce the projected increase in deaths from heat *[Very Likely, Very High Confidence]*.

Some Populations at Greater Risk

Key Finding 4: Older adults and children have a higher risk of dying or becoming ill due to extreme heat *[Very High Confidence]*. People working outdoors, the socially isolated and economically disadvantaged, those with chronic illnesses, as well as some communities of color, are also especially vulnerable to death or illness *[Very High Confidence]*.

2.1 Introduction

The Earth is warming due to elevated concentrations of greenhouse gases, and will continue to warm in the future. U.S. average temperatures have increased by 1.3°F to 1.9°F since record keeping began in 1895, heat waves have become more frequent and intense, and cold waves have become less frequent across the nation (see Ch. 1: Introduction). Annual average U.S. temperatures are projected to increase by 3°F to 10°F by the end of this century, depending on future emissions of greenhouse gases and other factors.[1] These temperature changes will have direct effects on human health.

Days that are hotter than the average seasonal temperature in the summer or colder than the average seasonal temperature in the winter cause increased levels of illness and death by compromising the body's ability to regulate its temperature or by inducing direct or indirect health complications. Figure 1 provides a conceptual model of the various climate drivers, social factors, and environmental and institutional factors that can interact to result in changes in illness and deaths as a result of extreme heat. Increasing concentrations of greenhouse gases lead to an increase of both average and extreme temperatures, leading to an increase in deaths and illness from heat and a potential decrease in deaths from cold. Challenges involved in determining the temperature–death relationship include a lack of consistent diagnoses on death certificates and the fact that the health implications of extreme temperatures are not absolute, differing from location to location and changing over time. Both of these issues can be partially addressed through the use of statistical methods. Climate model projections of future temperatures can be combined with the estimated relationships between temperatures and health in order to assess how deaths and illnesses resulting from temperature could change in the future. The impact of a warming climate on deaths and illnesses will not be realized equally as a number of populations, such as children, the elderly, and economically disadvantaged groups, are especially vulnerable to temperature.

Climate Change and Health—Extreme Heat

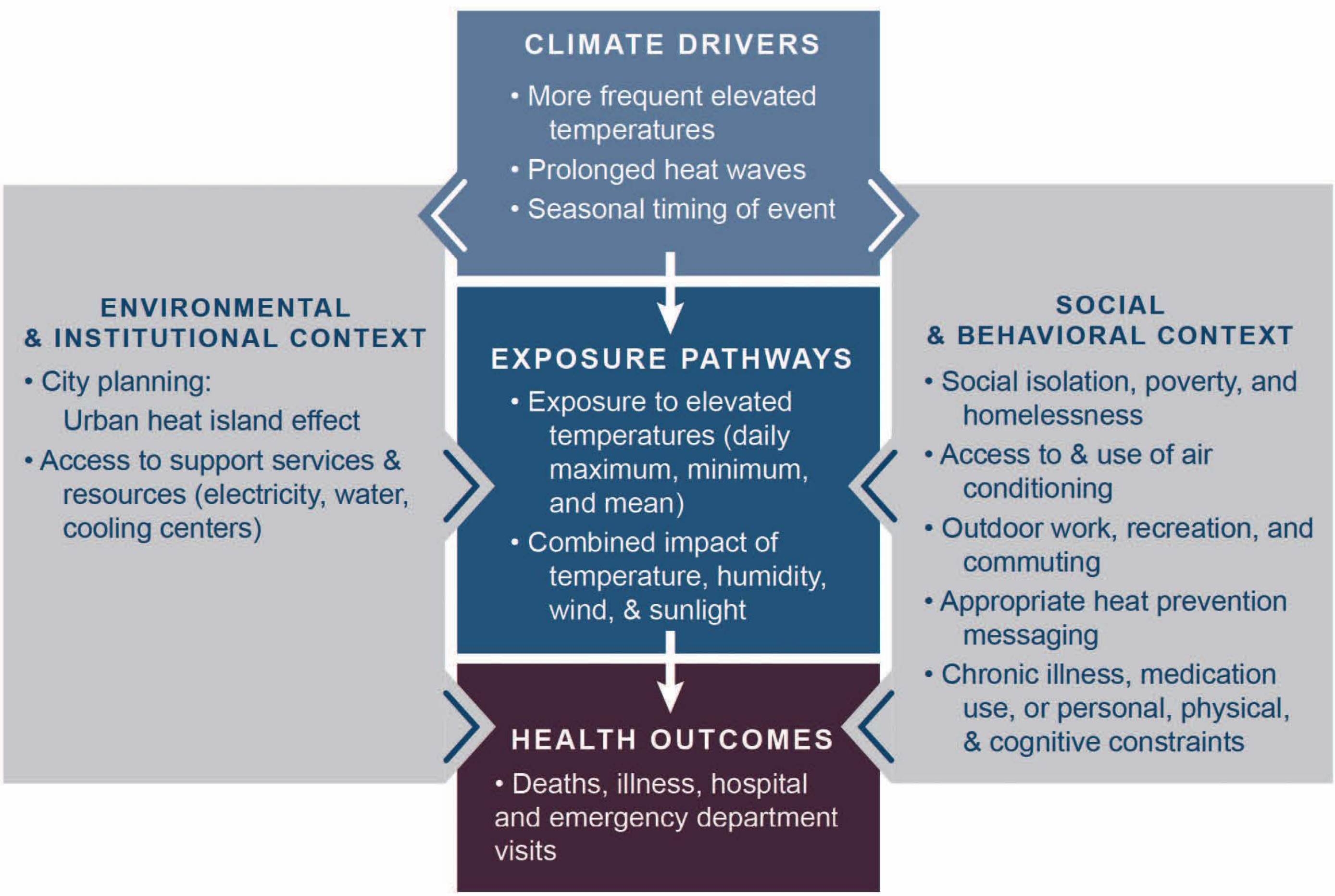


Figure 1: This conceptual diagram illustrates the key pathways by which climate change influences human health during an extreme heat event, and potential resulting health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box, and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. All of these influencing factors can affect an individual's or a community's vulnerability through changes in exposure, sensitivity, and adaptive capacity and may also be affected by climate change. See Chapter 1: Introduction for more information.

2.2 Contribution of Extreme Temperatures to Death and Illness

Temperature extremes most directly affect health by compromising the body's ability to regulate its internal temperature. Loss of internal temperature control can result in a cascade of illnesses, including heat cramps, heat exhaustion, heatstroke, and hyperthermia in the presence of extreme heat, and hypothermia and frostbite in the presence of extreme cold. Temperature extremes can also worsen chronic conditions such as cardiovascular disease, respiratory disease, cerebrovascular disease, and diabetes-related conditions. Prolonged exposure to high temperatures is associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders. Exposures to high minimum temperatures may also reduce the ability of the human body to recover from high daily maximum temperatures.

2.3 Defining Temperature Exposures

Extreme temperatures are typically defined by some measure, for example, an ambient temperature, heat index (a combination of temperature and humidity), or wind chill (a combination of temperature and wind speed), exceeding predefined thresholds over a number of days.[2, 3, 4, 5, 6, 7, 8] Extremes can be defined by average, minimum, or maximum daily temperatures, by nighttime temperatures, or by daytime temperatures. However, there is no standard method for defining a heat wave or cold wave. There are dramatic differences in the observed relationships between temperature, death, and illness across different regions and seasons; these relationships vary based on average temperatures in those locations and the timing of the heat or cold event. For example, a 95°F day in Vermont will have different implications for health than a 95°F day in Texas, and similarly, a 95°F day in May will have different implications than one in August[9, 10, 11, 12] (this is further discussed in "Evidence of Adaptation to Temperature Extremes" on page 49). Therefore, in some cases, temperature extremes are defined by comparison to some local average (for example, the top 1% of warmest days recorded in a particular location) rather than to some absolute temperature (such as 95°F). While temperature extremes are generally determined based on weather station records, the exposure of individuals will depend on their location: urban heat islands, microclimates, and differences between indoor and outdoor temperatures can all lead to differences between weather station data and actual exposure. The indoor environment is particularly important as most people spend the majority of their time inside.

> *Temperature extremes most directly affect health by compromising the body's ability to regulate its internal temperature.*

One exception to using relative measures of temperature is that there are some critical physical and weather condition thresholds that are absolute. For example, one combined measure of humidity and temperature is known as the wet bulb temperature. As the wet bulb temperature reaches or exceeds the threshold of 35°C (95°F), the human body can no longer cool through perspiration, and recent evidence suggests that there is a physical heat tolerance limit in humans to sustained temperatures above 35°C that is similar across diverse climates.[13] The combined effects of temperature and humidity have been incorporated in tools such as heat index tables, which reflect how combinations of heat and relative humidity "feel." The heat index in these tools is often presented with notes about the potential nature and type of health risks different combinations of temperature and humidity may pose, along with confounding conditions such as exposure to direct sunlight or strong winds.

Variations in heat wave definitions make it challenging to compare results across studies or determine the most appropriate public health warning systems.[8, 14] This is important as the associations between deaths and illnesses and extreme heat conditions vary depending on the methods used for defining the extreme conditions.[2, 15, 16]

2.4 Measuring the Health Impact of Temperature

Two broad approaches are used to study the relationship between temperatures and illness and death: direct attribution and statistical methods.[17, 18]

Direct Attribution Studies

With direct attribution, researchers link health outcomes to temperatures based on assigned diagnosis codes in medical records such as hospital admissions and death certificates. For example, the International Classification of Diseases (ICD-10) contains specific codes for attributing deaths to exposure to excessive natural heat (X30) and excessive natural cold (X31).[19] However, medical records will not include information on the weather conditions at the time of the event or preceding the event. It is generally accepted that direct attribution underestimates the number of people who die from temperature extremes. Reasons for this include difficulties in diagnosing heat-related and cold-related deaths, lack of consistent diagnostic criteria, and difficulty in identifying, or lack of reporting, heat or cold as a factor that worsened a preexisting medical condition.[9, 17] Heat-related deaths are often not reported as such if another cause of death exists and there is no well-publicized heat wave. An additional challenging factor in deaths classified as X31 (cold) deaths is that a number of these deaths result from situations involving substance use/abuse and/or contact with water, both of which can contribute to hypothermia.[20, 21]

Statistical Studies

Statistical studies measure the impact of temperature on death and illness using methods that relate the number of cases (for example, total daily deaths in a city) to observed weather conditions and other socio-demographic factors. These statistical methods determine whether the temperature conditions were associated with increased deaths or illness above longer-term average levels. These associations establish the relationship between temperature and premature deaths and illness. In some cases, particularly with extreme temperature conditions, the increase in premature deaths and illness can be quite dramatic and the health impact may be referred to in terms of excess deaths or illnesses. Methods for evaluating the impact of temperature in these models vary.

Many studies include all the days in the study period, which makes it possible to capture changes in deaths resulting from small variations of temperatures from their seasonal averages. Other methods restrict the analysis to days that exceed some threshold for extreme heat or cold conditions.[22] Some studies incorporate methods that determine different health relationships for wind, air pressure, and cloud cover as well as the more common temperature and humidity measures.[15] Another approach is to identify a heat event and compare observed illness and deaths during the event with a carefully chosen comparison period.[23, 24, 25] Many of these methods also incorporate socio-demographic factors (for example, age, race, and poverty) that may affect the temperature–death relationship.

Comparing Results of Direct Attribution and Statistical Studies

Comparing death estimates across studies is therefore complicated by the use of different criteria for temperature extremes, different analytical methods, varying time periods, and different affected populations. Further, it is widely accepted that characteristics of extreme temperature events such as duration, intensity, and timing in season directly affect actual death totals.[2, 12] Estimates of the average number of deaths attributable to heat and cold considering all temperatures, rather than just those associated with extreme events, provide an alternative for considering the mortality impact of climate change.[26, 27] Statistical studies can also offer insights into what aspects of a temperature extreme are most important. For example, there are indications that the relationship between high nighttime temperatures and mortality is more pronounced than the relationship for daytime temperatures.[12, 16]

These two methods (direct attribution and statistical approaches) yield very different results for several reasons. First, statistical approaches generally suggest that the actual number of deaths associated with temperature is far greater than those recorded as temperature-related in medical records. Medical records often do not capture the role of heat in exacerbating the cause of death, only recording the ultimate cause, such as a stroke or a heart attack (see, for example, Figure 2, where the excess deaths during the 1995 Chicago heat wave clearly exceeded the number of deaths recorded as heat-related on death certificates). Statistical methods focus on determining how temperature contributes to premature deaths and illness and therefore are not susceptible to this kind of undercount, though they face potential biases due to time-varying factors like seasonality. Both methods depend on temperatures measured at weather stations, though the actual temperature exposure of individuals may differ. In short, while the focus on temperature is consistent in both methods, the methods potentially evaluate very different combinations of deaths and weather conditions.

2.5 Observed Impact of Temperature on Deaths

A number of extreme temperature events in the United States have led to dramatic increases in deaths, including events in Kansas City and St. Louis in 1980, Philadelphia in 1993, Chicago in 1995, and California in 2006. (See Figure 2 for more on the July 1995 heat wave in Chicago).[28, 29, 30, 31, 32]

Recent U.S. studies in specific communities and for specific extreme temperature events continue to conclude that extreme temperatures, particularly extreme heat, result in premature deaths.[7, 30, 36, 37] This finding is further reinforced by a growing suite of regional- and national-scale studies documenting an increase in deaths following extreme temperature conditions, using both direct attribution[17] and statistical approaches.[9, 10, 12, 15, 38] The connection between heat events and deaths is also evident internationally. The European heat wave of 2003 is an especially notable example, as it is estimated to have been responsible for between 30,000 and 70,000 premature deaths.[39] However, statistical approaches find that elevated death rates are seen even for less extreme temperatures. These approaches find an optimal temperature, and show that there are more deaths at any temperatures that are higher or lower than that optimal temperature.[11, 40] Even though the increase in deaths per degree are smaller near the optimum than at more extreme temperatures, because the percentage of days that do not qualify as extreme are large,[41] it can be important to address the changes in deaths that occur for these smaller temperature differences.

A recent analysis of U.S. deaths from temperature extremes based on death records found an average of approximately 1,300 deaths per year from 2006 to 2010 coded as resulting from extreme cold exposures, and 670 deaths per year coded as resulting from exposure to extreme heat.[17] These results, and those from all similar studies that rely solely on coding within medical records to determine cause of deaths, will underestimate the actual number of deaths due to extreme temperatures.[17, 42] For example, some statistical approaches estimate that more than 1,300 deaths per year in the United

Heat-Related Deaths in Chicago in the Summer of 1995

Figure 2 illustrates an example of excess deaths following an extreme heat event. In this case, excess deaths are determined by calculating the difference between daily observed deaths in Chicago during the worst of the heat wave (starting on July 11) and longer-term daily averages for this time of year. The period of extreme heat extended from June 21 through August 10, 1995. Research into the event suggests it was the combination of high humidity, high daily maximum temperatures, and high daily minimum temperatures that made this event truly exceptional.[33] This event is estimated to have resulted in nearly 700 excess deaths in Chicago, based on a statistical approach.[35] By comparison, a direct attribution approach based on death certificates found only 465 deaths were attributed to extreme heat during this time period.[29] This kind of underestimate resulting from relying on death certificates is common. It is reasonable to expect that deaths may be even less likely to be attributed to extreme heat during a heat wave that, unlike the Chicago event, does not receive a great deal of public attention.

Heat-Related Deaths During the 1995 Chicago Heat Wave

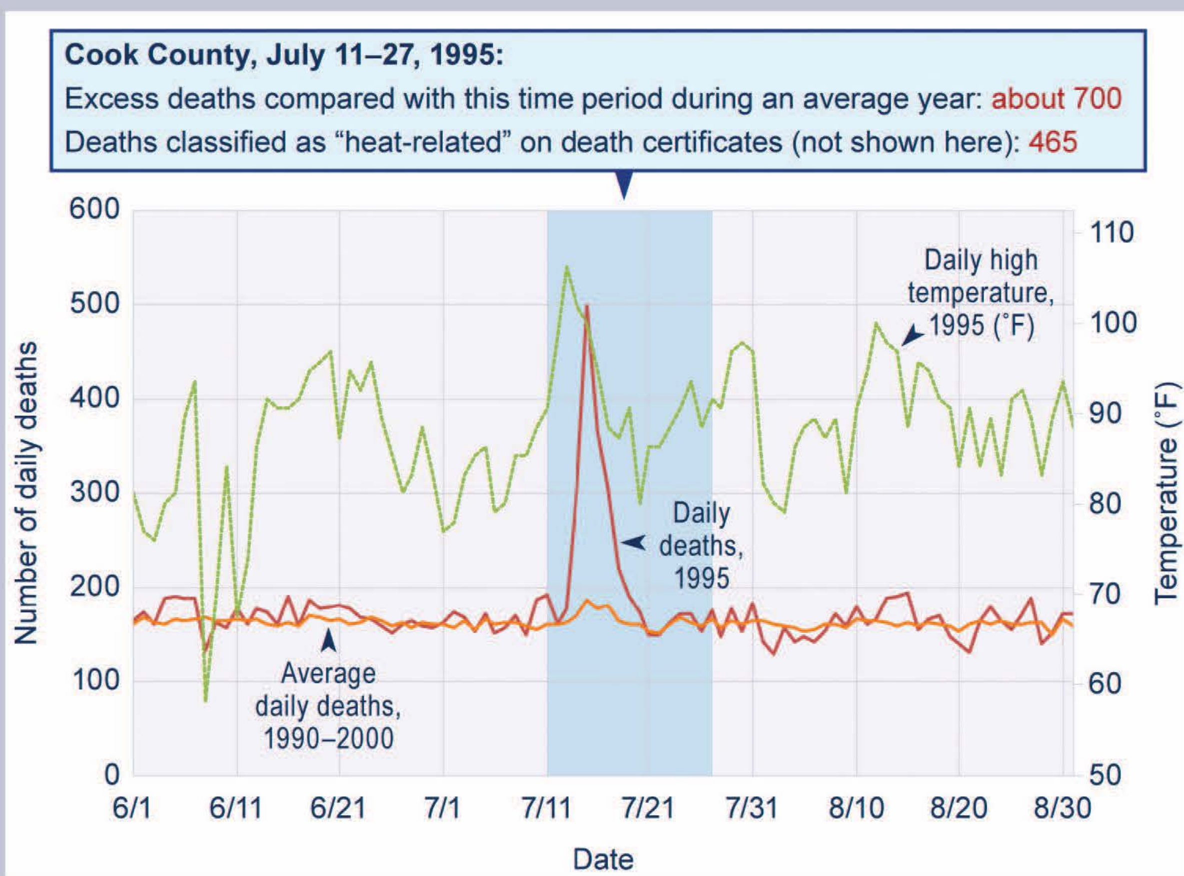


Figure 2: This figure shows the relationship between high temperatures and deaths observed during the 1995 Chicago heat wave. The large spike in deaths in mid-July of 1995 (red line) is much higher than the average number of deaths during that time of year (orange line), as well as the death rate before and after the heat wave. This increase in the rate of deaths occurred during and after the heat wave, as shown here by temperatures exceeding 100°F during the day (green line). Humidity and high nighttime temperatures were also key contributing factors to this increase in deaths.[33] The number of excess deaths has been estimated to be about 700 based on statistical methods, but only 465 deaths in Cook County were classified as "heat-related" on death certificates during this same period,[29] demonstrating the tendency of direct attribution to undercount total heat-related deaths. (Figure source: EPA 2014)[34]

States are due to extreme heat.[15, 43] Different approaches to attributing cause of death lead to differences in the relative number of deaths attributed to heat and cold.[44] Studies based on statistical approaches have found that, despite a larger number of deaths being coded as related to extreme cold rather than extreme heat, and a larger mortality rate in winter overall, the relationship between mortality and an additional day of extreme heat is generally much larger than the relationship between mortality and an additional day of extreme cold.[12]

Confounding Factors and Effect Modifiers

While the direct attribution approach underestimates the number of deaths resulting from extreme temperature events, there are a few ways in which the statistical approach may lead to an overestimation. However, any overestimation due to these potential confounding factors and effect modifiers is thought to be much smaller than the direct attribution underestimation.[12]

The first potential overestimation results from the connection between elevated temperatures and other variables that correlate with temperature, such as poor air quality. This connection involves a combination of factors, including stagnant air masses and changes in the atmospheric chemistry that affect the concentrations of air pollutants such as ozone or particulate matter (see Ch. 3: Air Quality Impacts). If some portion of the deaths during extreme heat events are actually a result of the higher levels of atmospheric pollution that are correlated with these events, then including those deaths in a statistical analysis to determine the relationship of increased heat on human health would result in double counting deaths.[10, 45, 46, 47] However, this issue is often addressed by including air pollution and other correlated variables in statistical modeling.[26]

A second consideration when using statistical approaches to determine the relationship between temperature and deaths is whether some of the individuals who died during the temperature event were already near death, and therefore the temperature event could be considered to have "displaced" the death by a matter of days rather than having killed a person not otherwise expected to die. This effect is referred to as mortality displacement. There is still no consensus regarding the influence of mortality displacement on premature death estimates, but this effect generally accounts for a smaller portion of premature deaths as events become more extreme.[7, 12, 48, 49, 50]

The relationship between mortality and an additional day of extreme heat is generally much larger than the relationship between mortality and an additional day of extreme cold.

Evidence of Adaptation to Temperature Extremes

The impact on human health of a given temperature event (for example, a 95°F day) can depend on where and when it occurs. The evidence also shows larger changes in deaths and hospitalizations in response to elevated temperatures in cities where temperatures are typically cooler as compared with warmer cities.[9, 11, 40, 51, 52] This suggests that people can adapt, at least partially, to the average temperature that they are used to experiencing. Some of this effect can be explained by differences in infrastructure. For example, locations with higher average temperature, such as the Southeast, will generally have greater prevalence and use of air conditioning. However, there is also evidence that there is a physiological acclimatization (the ability to gradually adapt to heat), with changes in sweat volume and timing, blood flow and heat transfer to the skin, and kidney function and water conservation occurring over the course of weeks to months of exposure to a hot climate.[53] For example, as a result of this type of adaptation, heat events later in the summer have less of an impact on deaths than those earlier in the summer, all else being equal,[15] although some of this effect is also due to the deaths of some of the most vulnerable earlier in the season. However, children and older adults remain vulnerable given their reduced ability to regulate their internal temperature and limited acclimatization capacities.[53]

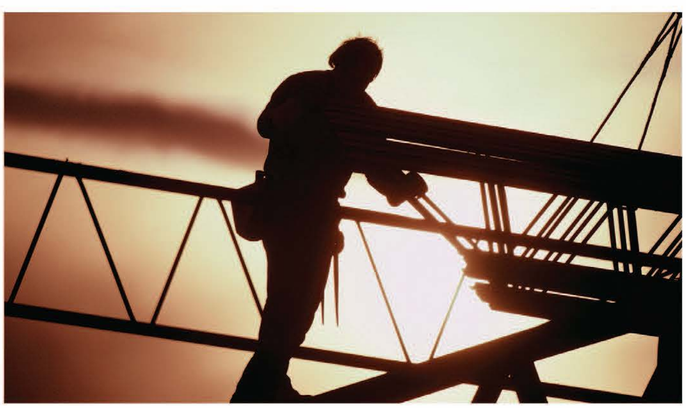
The impact on human health of a given temperature event (for example, a 95°day) can depend on where and when it occurs.

An increased tolerance to extreme temperatures has also been observed over multiyear and multidecadal periods.[9, 10, 54, 55, 56] This improvement is likely due to some combination of physiological acclimatization, increased prevalence and use of air conditioning,[10] and general improvements in public health over time,[9, 54] but the relative importance of each is not yet clear.[56]

Recent changes in urban planning and development programs reflect an adaptive trend implemented partially in response to the anticipated temperature health risks of climate change. For example, because urban areas tend to be warmer than surrounding rural areas (the "urban heat island" effect), there is an increased emphasis on incorporating green space and other technologies, such as cool roofs, in new development or redevelopment projects.[57] Similarly, programs that provide advice and services in preparation for or response to extreme temperatures continue to increase in number and expand the scope of their activity (see for example guidance documents on responses to extreme temperature developed by the Centers for Disease Control and Prevention and the Environmental Protection Agency).[58, 59] Continued changes in personal behavior as a result of these efforts, for example, seeking access to air-conditioned areas during extreme heat events or limiting outside activity, may continue to change future exposure to extreme temperatures and other climate-sensitive health stressors, such as outdoor air pollutants and vectors for disease such as ticks or mosquitoes.

Observed Trends in Heat Deaths

As discussed in Chapter 1, U.S. average temperature has increased by 1.3°F to 1.9°F since 1895, with much of that increase occurring since 1970, though this temperature increase has not been uniform geographically and some regions, such as the Southeast, have seen little increase in temperature and extreme heat over time.[1, 15] This warming is attributable to elevated concentrations of greenhouse gases and it has been estimated that three-quarters of moderately hot extremes are already a result of this historical warming.[60] As discussed in the previous section, there have also been changes in the tolerance of populations within the United States to extreme temperatures. Changes in mortality due to high temperatures are therefore a result of the combination of higher temperatures and higher heat tolerance. Use of the direct attribution approach, based on diagnosis codes in medical records, to examine national trends in heat mortality over time is challenging because of changes in classification methods over time.[34]



Certain occupational groups such as agricultural workers, construction workers, and electricity and pipeline utility workers are at increased risk for heat- and cold-related illness, especially where jobs involve heavy exertion.

The few studies using statistical methods that have presented total mortality estimates over time suggest that, over the last several decades, reductions in mortality due to increases in tolerance have outweighed increases in mortality due to increased temperatures.[15, 61]

2.6 Observed Impact of Temperature on Illness

Temperature extremes are linked to a range of illnesses reported at emergency rooms and hospitals. However, estimates for the national burden of illness associated with extreme temperatures are limited.

Using a direct attribution approach, an analysis of a nationally representative database from the Healthcare Utilization Project (HCUP) produced an annual average estimate of 65,299 emergency visits for acute heat illness during the summer months (May through September)—an average rate of 21.5 visits for every 100,000 people each year.[62] This result was based only on recorded diagnosis codes for hyperthermia and probably underestimates the true number of heat-related healthcare visits, as a wider range of health outcomes is potentially affected by extreme heat. For example, hyperthermia is not the only complication from extreme heat, and not every individual that suffers from a heat illness visits an emergency department. In a national study of Medicare patients from 2004 to 2005, an annual average of 5,004 hyperthermia cases and 4,381 hypothermia cases were reported for inpatient and outpatient visits.[63] None of these studies link health episodes to observed temperature data, thus limiting the opportunity to attribute these adverse outcomes to specific heat events or conditions.

High ambient heat has been associated with adverse impacts for a wide range of illnesses.[25] Examples of illnesses associated with extreme heat include cardiovascular, respiratory, and renal illnesses; diabetes; hyperthermia; mental health issues; and preterm births. Children spend more time outdoors and have insufficient ability for physiologic adaptation, and thus may be particularly vulnerable during heat waves.[64] Respiratory illness among the elderly population was most commonly reported during extreme heat.[65]

Statistical studies examine the association between extreme heat and illness using data from various healthcare access points (such as hospital admissions, emergency department visits, and ambulance dispatches). The majority of these studies examine the association of extreme heat with cardiovascular and respiratory illnesses. For these particular health outcomes, the evidence is mixed, as many studies observed elevated risks of illness during periods of extreme heat but others found no evidence of elevated levels of illness.[24, 51, 66, 67, 68, 69, 70] The evidence on some of the other health outcomes is more robust. Across emergency department visits and hospital admissions, high temperature have been associated with renal diseases, electrolyte imbalance, and hyperthermia.[24, 67,

[71, 72] These health risks vary not only across types of illness but also for the same illness across different healthcare settings. In general, evidence for associations with morbidity outcomes, other than cardiovascular impacts, is strong.

While there is still uncertainty about how levels of heat-related illnesses are expected to change with projected increases in summer temperature from climate change,[41] advances have been made in surveillance of heat-related illness. For example, monitoring of emergency ambulance calls during heat waves can be used to establish real-time surveillance systems to identify extreme heat events.[73] The increase in emergency visits for a wide range of illnesses during the 2006 heat wave in California points to the potential for using this type of information in real-time health surveillance systems.[24]

2.7 Projected Deaths and Illness from Temperature Exposure

Climate change will increase the frequency and severity of future extreme heat events while also resulting in generally warmer summers and milder winters,[1] with implications for human health. Absent further adaptation, these changes are expected to lead to an increase in illness and death from increases in heat, and reductions in illness and death resulting from decreases in cold, due to changes in outcomes such as heat stroke, cardiovascular disease, respiratory disease, cerebrovascular disease, and kidney disorders.[41, 74]

A warmer future is projected to lead to increases in future mortality on the order of thousands to tens of thousands of additional premature deaths per year across the United States by the end of this century.[22, 38, 54, 75, 76, 77, 78, 79] Studies differ in which regions of the United States are examined and in how they account for factors such as adaptation, mortality displacement, demographic changes, definitions of heat waves and extreme cold, and air quality factors, and some studies examine only extreme events while others take into account the health effects of smaller deviations from average seasonal temperatures. Despite these differences there is reasonable agreement on the magnitude of the projected changes. Additionally, studies have projected an increase in premature deaths due to increases in temperature for Chicago, IL,[39, 80] Dallas, TX,[18] the Northeast corridor cities of Boston, MA, New York, NY, and Philadelphia, PA,[18, 26, 81, 82] Washington State,[83, 84] California,[85] or a group of cities including Portland, OR; Minneapolis and St. Paul, MN; Chicago, IL; Detroit, MI; Toledo, Cleveland, Columbus, and Cincinnati, OH; Pittsburgh and Philadelphia, PA; and Washington, DC.[86] However, these regional projections use a variety of modeling strategies and therefore show more variability in mortality estimates than studies that are national in scope.

Less is known about how non-fatal illnesses will change in response to projected increases in heat. However, hospital admissions related to respiratory, hormonal, urinary, genital, and renal problems are generally projected to increase.[72, 87] Kidney stone prevalence has been linked to high temperatures, possibly due to dehydration leading to concentration of the salts that form kidney stones. In the United States, an increased rate of kidney stones is observed in southern regions of the country, especially the Southeast. An expansion of the regions where the risk of kidney stones is higher is therefore plausible in a warmer future.[88, 89, 90]

The decrease in deaths and illness due to reductions in winter cold have not been as well studied as the health impacts of increased heat, but the reduction in premature deaths from cold are expected to be smaller than the increase in deaths from heat in the United States.[22, 26, 38, 41, 75, 77] While this is true nationally (with the exception of Barreca 2012),[75] it may not hold for all regions within the country.[27] Similarly, international studies have generally projected a net increase in deaths from a warming climate, though in some regions, decreases in cold mortality may outweigh increases in heat mortality.[91] The projected net increase in deaths is based in part on historical studies that show that an additional extreme hot day leads to more deaths than an additional extreme cold day, and in part on the fact that the decrease in extreme cold deaths is limited as the total number of cold deaths approaches zero in a given location.

It is important to distinguish between generally higher wintertime mortality rates that are not strongly associated with daily temperatures—such as respiratory infections and some cardiovascular disease [12, 92]—from mortality that is more directly related to the magnitude of the cold temperatures. Some recent studies have suggested that factors leading to higher wintertime mortality rates may not be sensitive to climate warming, and that deaths due to these factors are expected to occur with or without climate change. Considering this, some estimates of wintertime mortality may overstate the benefit of climate change in reducing wintertime deaths.[49, 93, 94]

The U.S. population has become less sensitive to heat over time. Factors that have contributed to this change include infrastructure improvements, including increased access and use of air conditioning in homes and businesses, and improved societal responses, including increased access to public health programs and healthcare.[15, 54, 61, 95, 96, 97] Projecting these trends into the future is challenging, but this trend of increasing tolerance is projected to continue, with future changes in adaptive capacity expected to reduce the future increase in mortality.[56] However, there are limits to adaptation, whether physiological[53] or sociotechnical (for example, air conditioning, awareness programs, or cooling centers). While historically adaptation has outpaced warming, most studies project a future increase in mortality even when including assumptions regarding adaptation.[18, 22, 81, 85, 91] Additionally, the occurrence of events such as power outages simultaneous with a heat wave may reduce some of these adaptive benefits. Such simultaneous events can

Research Highlight: Modeling the Effect of Warming on U.S. Deaths

Importance: A warming climate is expected to result in more days that are warmer than today's usual temperature in the summer, leading to an increase in heat-related deaths. A warming climate is also expected to result in fewer days that are colder than today's usual temperatures in the winter, leading to a decrease in cold-related deaths. Understanding these changes is an important factor in understanding the human health response to climate change.

Objective: A quantitative projection of future deaths from heat and cold for 209 U.S. cities with a total population of over 160 million inhabitants.

Method: A relationship between average daily temperature and deaths by city and month was developed using historical data on deaths and temperatures from 1996–2006, generating results for both same-day temperature and the average of the previous five-day temperatures to account for delayed responses to temperature. Cities, which are defined using county borders, were allocated to nine different clusters based on similarity of climates. Temperature–death relationships were refined for cities within a given cluster based on the other cities in that cluster. Projections of temperature in future time periods were based on the RCP6.0 scenario from two climate models: the Geophysical Fluid Dynamic Laboratory–Coupled Physical Model 3 (GFDL–CM3) and the Model for Interdisciplinary Research on Climate (MIROC5). These projections were adjusted to match the historical data from the same weather stations that were used in the statistical analysis. Further details can be found in Schwartz et al. 2015.[27]

Projected Changes in Temperature-Related Death Rates

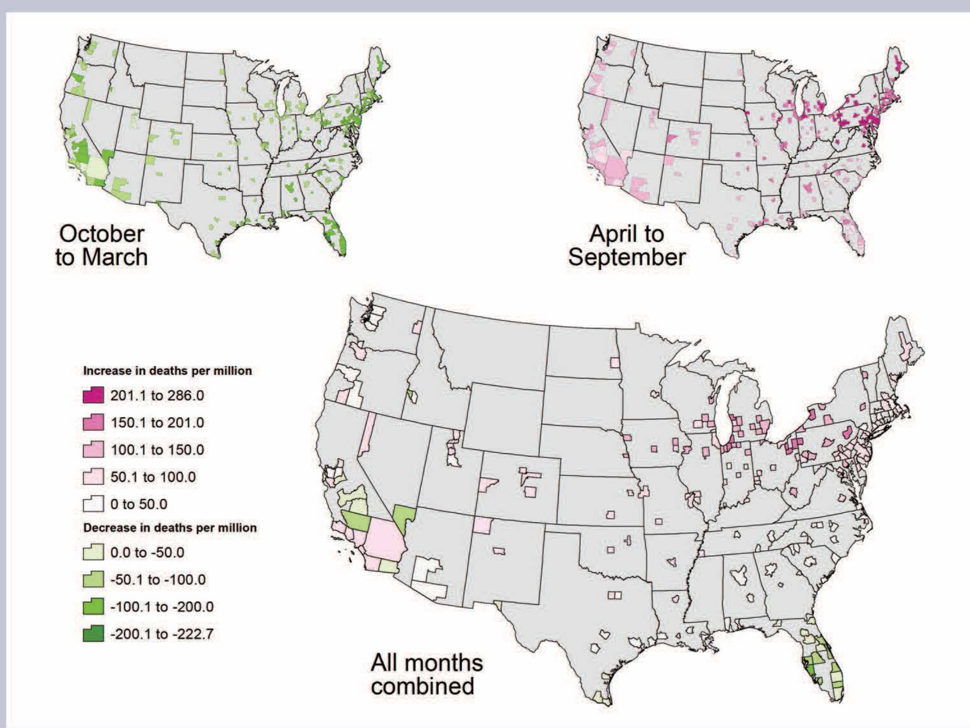


Figure 3: This figure shows the projected decrease in death rates due to warming in colder months (October–March, top left), the projected increase in death rates due to warming in the warmer months (April–September, top right), and the projected net change in death rates (combined map, bottom), comparing results for 2100 to those for a 1990 baseline period in 209 U.S. cities. These results are from one of the two climate models (GFDL–CM3 scenario RCP6.0) studied in Schwartz et al. (2015). In the study, mortality data for a city is based on county-level records, so the borders presented reflect counties corresponding to the study cities. Geographic variation in the death rates are due to a combination of differences in the amount of projected warming and variation in the relationship between deaths and temperatures derived from the historical health and temperature data. These results are based on holding the 2010 population constant in the analyses, with no explicit assumptions or adjustment for potential future adaptation. Therefore, these results reflect only the effect of the anticipated change in climate over time. (Figure source: Schwartzet al. 2015)[27]

Research Highlight: Modeling the Effect of Warming on U.S. Deaths, continued

Results: The modeling done for this study projects that future warming, without any adjustments for future adaptation, will lead to an increase in deaths during hotter months, defined as April–September, and a decrease in deaths during colder months, defined as October–March. Overall, this leads to a total net increase of about 2,000 to 10,000 deaths per year in the 209 cities by the end of the century compared to a 1990 baseline (Figure 4). Net effects vary from city to city, and a small number of cities are projected to experience a decrease in deaths (Figures 3 and 4).

Conclusions: This study is an improvement on previous studies because it examines a greater proportion of the U.S. population, uses more recent data on deaths, takes advantage of similar relationships between deaths and temperature between nearby cities to generate more statistically robust results, and addresses the difference in these relationships by month of the year. The results are consistent with most of the previous studies in projecting that climate change will lead to an increase in heat deaths on the order of thousands to tens of thousands of annual deaths by the end of the century compared to the 1990 baseline, and that the increase in deaths from heat will be larger than the reduction in deaths from cold. In contrast to some previous similar studies,[22] some individual cities show a net reduction in future deaths due to future warming, mainly in locations where the population is already well-adapted to heat but poorly prepared for cold (like Florida). Barreca 2012[75] also shows net mortality benefits in some counties, though with a different spatial pattern due to humidity effects. Some other studies also have different spatial patterns, projecting high excess mortality in Southern states despite a lower risk per degree change, due to larger increases in frequency and duration of heat waves in that region.[79] Like most previous studies, this analysis does not account for the effects of further adaptation on future mortality. Results are based on the temperature–death relationships observed for the period from 1996 to 2006, which reflect historical adaptation to extreme temperatures. However, future adaptation would, all else equal, mean that these results may overestimate the potential impact of climate change on changes in both heat- and cold-related deaths.

This study increases the confidence in the key finding that the number of heat deaths will increase in the future compared to a future with no climate change, and that the increase in heat deaths will be larger than the reduction in cold deaths.

Projected Changes in Deaths in U.S. Cities by Season

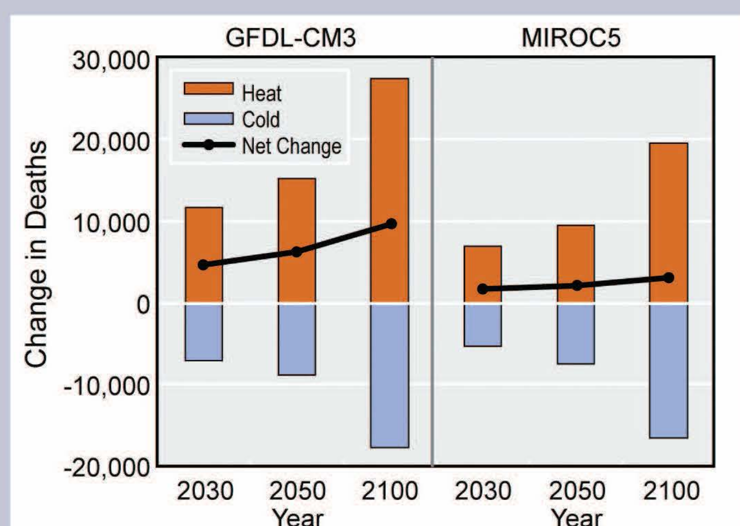


Figure 4: This figure shows the projected increase in deaths due to warming in the summer months (hot season, April–September), the projected decrease in deaths due to warming in the winter months (cold season, October–March), and the projected net change in deaths for the 209 U.S. cities examined. These results compare projected deaths for future reporting years to results for the year 1990 while holding the population constant at 2010 levels and without any quantitative adjustment for potential future adaptation, so that temperature–death relationships observed in the last decade of the available data (1997–2006) are assumed to remain unchanged in projections over the 21st century.
With these assumptions, the figure shows an increasing health benefit in terms of reduced deaths during the cold season (October–March) over the 21st century from warming temperatures, while deaths during the hot season (April–September) increase. Overall, the additional deaths from the warming in the hot season exceed the reduction in deaths during the cold season, resulting in a net increase in deaths attributable to temperature over time as a result of climate change. The baseline and future reporting years are based on 30-year periods where possible, with the exception of 2100: 1990 (1976–2005), 2030 (2016–2045), 2050 (2036–2065), and 2100 (2086–2100). (Figure source: adapted from Schwartz et al. 2015)[27]

be more common because of the additional demand on the electricity grid due to high air-conditioning usage.[98] Another potential effect is that if current trends of population growth and migration into large urban areas continue, there may be an increasing urban heat island effect which will magnify the rate of warming locally, possibly leading to more heat-related deaths and fewer cold-related deaths.

Projected changes in future health outcomes associated with extreme temperatures can be difficult to quantify. Projections can depend on 1) the characterization of population sensitivity to temperature event characteristics such as magnitude, duration, and humidity; 2) differences in population sensitivity depending on the timing and location of an extreme event; 3) future changes in baseline rates of death and illness as well as human tolerance and adaptive capacity; 4) the changing proportions of vulnerable populations, including the elderly, in the future; and 5) uncertainty in climate projections.

2.8 Populations of Concern for Death and Illness from Extreme Temperatures

Impacts of temperature extremes are geographically varied and disproportionally affect certain populations of concern (see also Ch. 9: Populations of Concern).[41] Certain populations are more at risk for experiencing detrimental consequences of exposure to extreme temperatures due to their sensitivity to hot and cold temperatures and limitations to their capacity for adapting to new climate conditions.

Older adults are a rapidly growing population in the United States, and heat impacts are projected to occur in places where older adults are heavily concentrated and therefore most exposed.[99] Older adults are at higher risk for temperature-related mortality and morbidity, particularly those who have preexisting diseases, those who take certain medications that affect thermoregulation or block nerve impulses (for example, beta-blockers, major tranquilizers, and diuretics), those who are living alone, or those with limited mobility (see also Ch. 9: Populations of Concern).[17, 24, 42, 45, 100] The relationship between increased temperatures and death in older adults is well-understood with strong evidence of heat-related vulnerability for adults over 65 and 75 years old.[101] An increased risk for respiratory and cardiovascular death is observed in older adults during temperature extremes due to reduced thermoregulation.[17, 42, 45, 65] Morbidity studies have also identified links between increased temperatures and respiratory and cardiovascular hospitalizations in older adults.[65]

Children are particularly vulnerable because they must rely on others to help keep them safe. This is especially true in environments that may lack air conditioning, including homes, schools, or cars (see also Ch. 9: Populations of Concern).[102] The primary health complications observed in children exposed to extreme heat include dehydration, electrolyte imbalance, fever, renal disease, heat stress, and hyperthermia.[64] Infectious and respiratory diseases in children are affected by both hot and cold temperatures.[64] Inefficient thermoregulation, reduced cardiovascular output, and heightened metabolic rate are physiological factors driving vulnerability in children to extreme heat. Children also spend a considerable amount of time outdoors and participating in vigorous physical activities.[17, 42, 64, 103] High-school football players are especially vulnerable to heat illness (see also Ch. 9: Populations of Concern).[104] A limited number of studies show evidence of cold-related mortality in children. However, no study has examined the relationship between cold temperature and cause-specific mortality.[64] Pregnant women are also vulnerable to temperature extremes as preterm birth has been associated with extreme heat.[42, 105, 106] Elevated heat exposure can increase dehydration, leading to the release of labor-inducing hormones.[107] Extreme heat events are also associated with adverse birth outcomes, such as low birth weight and infant mortality (see Ch. 9: Populations of Concern).

Physiological factors and participation in vigorous outdoor activities make children particularly vulnerable to extreme heat.

Where a person lives, works, or goes to school can also make them more vulnerable to health impacts from extreme temperatures. Of particular concern for densely populated cities is the urban heat island effect, where manmade surfaces absorb sunlight during the day and then radiate the stored energy at night as heat. This process will exacerbate any warming from climate change and limit the potential relief of cooler nighttime temperatures in urban areas.[81] In addition to the urban heat island effect, land cover characteristics and poor air quality combine to increase the impacts of high ambient temperatures for city dwellers and further increase the burden on populations of concern within the urban area.[12, 17, 45, 108] The homeless are often more exposed to heat and cold extremes, while also sharing many risk factors with other populations of concern such as social isolation, psychiatric illness, and other health issues.[109]

Race, ethnicity, and socioeconomic status can affect vulnerability to temperature extremes. Non-Hispanic Black persons

have been identified as being more vulnerable than other racial and ethnic groups to detrimental consequences of exposure to temperature extremes.[17, 42, 45, 103, 110, 111] One study found that non-Hispanic Blacks were 2.5 times more likely to experience heat-related mortality compared to non-Hispanic Whites, and non-Hispanic Blacks had a two-fold risk of dying from a heat-related event compared to Hispanics.[17] Evidence of racial differences in heat tolerance due to genetic differences is inconclusive.[110] However, other factors may contribute to increased vulnerability of Black populations, including comorbidities (co-existing chronic conditions) that increase susceptibility to higher temperatures, disparities in the availability and use of air conditioning and in heat risk-related land cover characteristics (for example, living in urban areas prone to heat-island effects), and environmental justice issues.[17, 42, 108, 110, 112] Overall, the link between temperature extremes, race, ethnicity, and socioeconomic status is multidimensional and dependent on the outcome being studied. Education level, income, safe housing, occupational risks, access to health care, and baseline health and nutrition status can further distort the association between temperature extremes, race, and ethnicity.[45, 110]

Outdoor workers spend a great deal of time exposed to temperature extremes, often while performing vigorous activities. Certain occupational groups such as agricultural workers, construction workers, and electricity and pipeline utility workers are at increased risk for heat- and cold-related illness, especially where jobs involve heavy exertion.[100, 113, 114] One study found failure of employers to provide for acclimatization to be the factor most clearly associated with heat-related death in workers.[113]

Mental, behavioral, and cognitive disorders can be triggered or exacerbated by heat waves. Specific illnesses impacted by heat include dementia, mood disorders, neurosis and stress, and substance abuse.[100, 115, 116, 117] Some medications interfere with thermoregulation, thereby increasing vulnerability to heat.[116] One study in Australia found that hospital admissions for mental and behavioral disorders increased by 7.3% during heat waves above 80°F.[115] Studies have also linked extreme heat and increased aggressive behavior. (See also Ch. 8: Mental Health).

2.9 Emerging and Cross-Cutting Issues

Emerging and cross-cutting issues include 1) disparate ways that extreme temperature and health are related, 2) urban and rural differences, 3) interactions between impacts and future changes in adaptation, and 4) projections of extreme temperature events.

The health effects addressed in this chapter are not the only ways in which heat and health are related. For example, research indicates that hotter temperatures may lead to an increase in violent crime[118] and could negatively affect the labor force, especially occupational health for outdoor sectors.[119, 120] Extreme temperatures also interact with air quality, which can complicate estimating how extreme temperature events impact human health in the absence of air quality changes (see "Confounding Factors and Effect Modifiers" on page 49). In addition, increased heat may also increase vulnerability to poor air quality and allergens, leading to potential non-linear health outcome responses. Extreme temperature events, as well as other impacts from climate change, can also be associated with changes in electricity supply and distribution that can have important implications for the availability of heating and air conditioning, which are key adaptive measures.

Though the estimates of the health impact from extreme heat discussed in the “Research Highlight” were produced only for urban areas (which provided a large sample size for statistical validity), there is also emerging evidence regarding high rates of heat-related illness in rural areas.[6, 62] Occupational exposure and a lack of access to air conditioning are some of the factors that may make rural populations particularly susceptible to extreme heat. There are quantitative challenges to using statistical methods to estimate mortality impacts of temperatures in rural areas due to lower population density and more dispersed weather stations, but rural residents have also demonstrated vulnerability to heat events.[121]

Other changes in human behavior will also have implications for the linkage between climate and heat-related illness. Changes in building infrastructure as a response to changes in temperature can have impacts on indoor air quality. Similarly, changes in behavior as a result of temperature changes, for example, seeking access to air conditioning, can change exposure to indoor and outdoor pollution and vectorborne diseases (see Ch. 3: Air Quality Impacts; Ch. 5: Vectorborne Diseases).

Finally, projecting climate variability and the most extreme temperature events can be more challenging than projecting average warming. Extreme temperatures may rise faster than average temperatures,[122] with the coldest days warming faster than average for much of the twentieth century, and the warmest days warming faster than average temperatures in the past 30 years.[123] Extremely high temperatures in the future may also reach levels outside of past experience, in which case statistically based relationships may no longer hold for those events. There have been suggestive links between rapid recent Arctic sea ice loss[124] and an increased frequency of cold[125] and warm extremes,[126] but this is an active area of research with conflicting results.[127, 128] In regions where temperature variability increases, mortality will be expected to increase; mortality is expected to decrease in regions where variability decreases.[129]

2.10 Research Needs

In addition to the emerging issues identified above, the authors highlight the following potential areas for additional scientific and research activity on temperature-related illness and death based on their review of the literature. Improved modeling and more robust projections of climate variability and extreme temperatures will enhance the modeling of health impacts associated with extremes of heat and cold. While the surveillance for temperature-related deaths is relatively robust, understanding the impacts of future changes in heat waves and extreme temperatures can be improved with better surveillance and documentation of non-fatal illnesses, including hospitalizations and emergency room visits, for temperature-associated reasons. With growing implementation of heat early warning systems around the country, there is also a need for the development of evaluation methods and associated collection of data to be able to assess effectiveness of such systems and other means of health adaptation.

Future assessments can benefit from research activities that:

- further explore the associations between exposure to a range of high and low temperatures and exacerbation of illnesses across locations and healthcare settings;
- improve understanding of how genetic factors and social determinants contribute to vulnerability to illness and death from extreme temperature exposures;
- analyze the combined health effects of temperature and other discrete climate-sensitive stressors, such as changing air quality, smoke from wildfires, or impacts of extreme weather events;
- attribute changes in observed mortality to a changing climate;
- develop effective adaptive responses to reduce the potential adverse health outcomes attributable to changing temperatures; and
- explore how future adaptive measures and behaviors can be included in quantitative models of health impacts associated with extreme temperatures

Supporting Evidence

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops, teleconferences, and email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, and Federal agencies. For additional information on the overall report process, see Appendices 2 and 3.

The content of this chapter was determined after reviewing the collected literature. The authors determined that there was substantial literature available to characterize both observed and projected mortality from elevated temperatures, with sufficient literature available to also characterize mortality from cold as well as cold-related hospitalizations and illness. Populations of concern were also considered to be a high priority for this chapter. As discussed in the chapter, there were limitations in terms of the state of the literature on understanding how future adaptation will influence climate-related changes in temperature-related mortality, addressing the impact of temperature on rural populations, and examining health-related endpoints other than mortality and morbidity.

KEY FINDING TRACEABLE ACCOUNTS

Future Increases in Temperature-Related Deaths

Key Finding 1: Based on present-day sensitivity to heat, an increase of thousands to tens of thousands of premature heat-related deaths in the summer *[Very Likely, High Confidence]* and a decrease of premature cold-related deaths in the winter *[Very Likely, Medium Confidence]* are projected each year as a result of climate change by the end of the century. Future adaptation will very likely reduce these impacts (see Changing Tolerance to Extreme Heat Finding). The reduction in cold-related deaths is projected to be smaller than the increase in heat-related deaths in most regions *[Likely, Medium Confidence]*.

Description of evidence base

An extensive literature examines projections of mortality due to increasing temperatures. In particular, nine studies were identified that provide heat mortality projections in the United States for at least 10% of the U.S. population.[22, 27, 38, 54, 75, 76, 77, 78, 79] Each of these studies projected an increase in heat-related mortality due to projections of future warming, though several noted the potential modification effect of adaptation (discussed in Key Finding #3). In general, the magnitude of projected increases in annual premature deaths in these studies was in the hundreds to thousands by mid-century, and thousands to tens of thousands by the end of the century, when scaled to the total U.S. population. These conclusions are further supported by studies at the city, county, and state level.[18, 26, 39, 80, 81, 82, 83, 84, 85]

The Third National Climate Assessment (2014 NCA) found that "While deaths and injuries related to cold events are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths,"[41] and studies published since that time have further supported this finding. Of those studies that examine both heat and cold at the national scale, only Barreca found that the reductions in cold deaths would more than compensate for the increase in heat deaths.[22, 27, 38, 75, 77] Barreca's study was novel in terms of its treatment of humidity, finding that weather that was both cold and dry, or both hot and humid, was associated with higher mortality. However, this treatment of humidity was not the cause of the difference with other studies, as leaving out humidity actually showed a greater benefit from future climate change. Instead, the author stated that the reduction in net deaths was a result of relying on counties with over 100,000 inhabitants, and that using a state-level model covering all U.S. deaths would lead to a prediction of an increase of 1.7% in mortality rates rather than a decrease of 0.1%. The finding by the majority of studies at a national scale that heat deaths will increase more than cold deaths will decrease is consistent with studies at smaller spatial scales.[26] Moreover, several studies provide rationales for why heat mortality is expected to outpace cold mortality,[12, 22, 27] and some studies suggest that cold mortality may not be responsive to warming.[49, 93, 94] Barnett et al. (2012) showed that cold waves were not generally associated with an increase in deaths beyond the mortality already associated with cold weather, in contrast to heat waves.[2]

Major uncertainties

The largest remaining uncertainties concern questions of future adaptation, which are discussed in Key Finding #3. A related uncertainty involves the link between the temperatures measured at weather stations and the temperatures experienced by individuals. As long as the relationship between the weather station and the microclimate or indoor/outdoor difference remains constant, this should not impair projections. However, as microclimates, building construction, or behavior change, the relationship between recorded weather station temperature and actual temperature exposure will change. This is related to, but broader than, the question of adaptation. Additionally, there are uncertainties regarding the non-linearities of heat response with increasing temperatures.

Assessment of confidence and likelihood based on evidence

There is **high confidence** that heat deaths will **very likely** increase in the future compared to a future without climate change, based on high agreement and a large number of studies as well as consistency across scenarios and regions. Because there are fewer studies on winter mortality, and because studies exist that suggest that winter mortality is not strongly linked to temperatures, there is **medium confidence** that deaths due to extreme cold will **very likely** decrease. The majority of the studies that examine both heat and cold deaths find that the increase in heat deaths due to climate change will **likely** be larger than the decrease in cold deaths in most regions, but there are a limited number of such studies, leading to an assessment of **medium confidence**.

Even Small Differences from Seasonal Average Temperatures Result in Illness and Death

Key Finding 2: Days that are hotter than usual in the summer or colder than usual in the winter are both associated with increased illness and death *[Very High Confidence]*. Mortality effects are observed even for small differences from seasonal average temperatures *[High Confidence]*. Because small temperature differences occur much more frequently than large temperature differences, not accounting for the effect of these small differences would lead to underestimating the future impact of climate change *[Likely, High Confidence]*.

Description of evidence base

Two well-recognized conclusions from the literature are that extreme temperatures lead to illness and premature death and that these extreme temperatures are best described in relation to local average seasonal temperatures rather than absolute temperature values. Epidemiological studies find an increase in mortality at temperatures that are high related to the local average.[9, 10, 12, 15, 17, 38] Based on absolute temperatures, Anderson and Bell 2011 found that cities in the South and Southeast were the least sensitive to heat, demonstrating acclimatization.[9]

Illness has been linked with hot daily average temperature[4, 6, 51, 69, 71] and apparent temperature, among other metrics.[3, 66, 68, 87] Across studies, adverse health episodes were most strongly associated with exposures to high temperatures that occurred on the same day or the previous day.[3, 51] However, a cumulative effect of heat was also observed at periods of up to one week after exposure, tapering off beyond seven days.[69, 105] Cardiovascular and respiratory illness has been most commonly examined in relation to extreme heat, but the association is more varied for illness than for mortality due to effects across age groups[69, 70] and differences in morbidity risk associated with emergency room records versus hospital admissions.[4, 6, 24, 51, 66, 67, 68, 69, 70]

The evidence for mortality is clearest for extreme temperatures, as addressed in threshold-based studies,[12] but studies that account for smaller changes in temperature found mortality changes even for small deviations of temperature.[11, 27] This is consistent with studies showing a U-shaped relationship of temperature and mortality—while there may be some plateau near the optimal temperature, the plateau is often small, and not always coincident with the seasonal average temperature.[11, 40] However, some of the individuals who die in response to elevated temperatures were already near death, and so the temperature event is sometimes considered to have "displaced" the death by a matter of days rather than created an additional death. Studies have found that this effect is generally below 50% of the total deaths, and is much smaller than that (10% or less) for the most extreme events, such as the 2003 European heat wave.[12, 48, 49, 50] In contrast, one recent study found that in seven U.S. cities mortality displacement was greater than 80% for small temperature deviations and around 50% even for the 3% of warmest events in the study sample.[7]

Major uncertainties

This finding reflects consideration of a number of recent studies[17, 54] not referenced in the recent 2014 NCA.[41] There is a consensus of studies linking extreme temperatures and mortality, and a growing body of literature demonstrating that smaller differences in temperature are also linked with mortality. However, the mortality displacement effect, and the fact that deaths that do not occur during an identified heat wave are less likely to be directly attributed to extreme heat, contribute to continuing uncertainty about the magnitude of the effect of temperature on mortality.

Assessment of confidence and likelihood based on evidence

There is **very high confidence** in the relationship between extreme temperatures and premature deaths due to the consistency and strength of the literature, particularly given the different study designs that produce this result. There is **high confidence** that small temperature deviations from normal temperatures contribute to premature mortality due to high agreement among those studies that have examined the issue. Though some studies indicate that for these small temperature differences, mortality displacement may play a larger role than for more extreme temperatures. Fewer studies have examined the role of these smaller temperature differences in projections, but the directionality of the effect is clear, so the determination of the authors was that not including this effect would likely lead to an underestimate of future mortality, with **high confidence**.

Changing Tolerance to Extreme Heat

Key Finding 3: An increase in population tolerance to extreme heat has been observed over time *[Very High Confidence]*. Changes in this tolerance have been associated with increased use of air conditioning, improved social responses, and/or physiological acclimatization, among other factors *[Medium Confidence]*. Expected future increases in this tolerance will reduce the projected increase in deaths from heat *[Very Likely, Very High Confidence]*.

Description of evidence base

The increasing tolerance of the U.S. population to extreme heat has been shown by a number of studies.[9, 10, 54] However, there is less confidence in attributing this increase in tolerance: increased prevalence and use of air conditioning, physiological adaptation, available green space, and improved social responses have all been proposed as explanatory factors. There have been some indications (Sheridan et al. 2009)[97] that tolerance improvements in the United States might have plateaued, but Bobb et al. 2014 found continuing improvements through 2005.[54]

Several approaches to including adaptation have been used in temperature mortality projection studies. For example, two studies used an "analog city" approach, where the response of the population to future temperatures in a given city is assumed to be equal to that of a city with a hotter present-day climate.[22, 81] Another approach is to assume that critical temperature thresholds change by

some quantity over time.[18, 91] A third approach is to calculate sensitivity to air conditioning prevalence in the present, and make assumptions about air conditioning in the future.[85] In general, inclusion of adaptation limits the projected increase in deaths, sometimes modestly, other times dramatically. However, approaches used to account for adaptation may be optimistic. Historically, adaptive measures have occurred as a response to extreme events, and therefore could be expected to lag warming.[39, 96] While the increase in mortality projected in these studies is reduced, the studies generally found that mortality increases compared to present day even under optimistic adaptation assumptions.[18, 22, 81, 85] A limit to adaptation may be seen in that even in cities with nearly 100% air conditioning penetration, heat deaths are observed today.

Major uncertainties

While studies have been published in recent years that include adaptation in sensitivity analyses,[22] this remains a challenging area of research. Difficulties in attributing observed increases in tolerance make it challenging to project future changes in tolerance, whether due to autonomous adaptation by individuals or planned adjustments by governments. Extrapolation of acclimatization is limited as there must be an increase in temperature beyond which acclimatization will not be possible.

Assessment of confidence and likelihood based on evidence

There is **very high confidence** that a decrease in sensitivity to heat events has occurred based on high agreement between studies, but only **medium confidence** that this decrease is due to some specific combination of air conditioning prevalence, physiological adaptation, presence of green space, and improved social responses because of the challenges involved in attribution. There is **very high confidence** that mortality due to heat will **very likely** be reduced compared to a no-adaptation scenario when adaptation is included, because all studies examined were in agreement with this conclusion, though the magnitude of this reduction is poorly constrained.

Some Populations at Greater Risk

Key Finding 4: Older adults and children have a higher risk of dying or becoming ill due to extreme heat *[Very High Confidence]*. People working outdoors, the socially isolated and economically disadvantaged, those with chronic illnesses, as well as some communities of color, are also especially vulnerable to death or illness *[Very High Confidence]*.

Description of evidence base

The relationship between increased temperatures and deaths in elderly populations is well-understood. An increased risk of respiratory and cardiovascular death is observed in elderly populations during temperature extremes due to reduced thermoregulation.[17, 42, 45, 65]

Studies cite dehydration, electrolyte imbalance, fever, heat stress, hyperthermia, and renal disease as the primary health conditions in children exposed to heat waves. Causes of heat-related illness in children include inefficient thermoregulation, reduced cardiovascular output, and heightened metabolic rate. Children also spend a considerable amount of time outdoors and participating in vigorous activities.[17, 42, 64, 103] A limited number of studies found evidence of cold-related mortality in children; however, no study has examined the relationship between cold temperature and cause-specific mortality.[64]

Certain occupational groups that spend a great deal of time exposed to extreme temperatures, such as agricultural workers, construction workers, and electricity and pipeline utility workers, are at increased risk for heat- and cold-related illness, especially where jobs involve heavy exertion.[100, 113, 114] Lack of heat-illness-prevention programs in the workplace that include provisions for acclimatization was found to be a factor strongly associated with extreme temperature-related death.[113]

Race, ethnicity, and socioeconomic status have been shown to impact vulnerability to temperature extremes. Several studies have identified non-Hispanic Black populations to be more vulnerable than other racial and ethnic groups for experiencing detrimental consequences of exposure to temperature extremes.[17, 42, 45, 103, 110] Studies suggest comorbidities that enhance susceptibility to higher temperatures, availability and use of air conditioning, disparities in heat risk-related land cover characteristics, and other environmental justice issues contribute to increased vulnerability of non-Hispanic Blacks.[17, 42, 108, 110, 112]

Dementia, mood disorders, neurosis and stress-related illnesses, and substance abuse are shown to be impacted by extreme heat.[100, 115, 116, 117] Some medications interfere with thermoregulation, increasing vulnerability to heat.[116]

Major uncertainties

The literature available at the time of the development of the 2014 NCA had identified a number of vulnerable populations that were disproportionately at risk during heat waves, and literature since that time has only strengthened the understanding of the elevated risks for these populations. There continues to be a need for better understanding of the relative importance of genetics and environmental justice issues with regards to the observed higher risk for non-Hispanic Blacks, more work on understanding the risks to pregnant women from extreme temperature events, and a better understanding of the relationship between extreme cold vulnerabilities in populations of concern.

Assessment of confidence and likelihood based on evidence

Although some details regarding causation and identifying the most vulnerable subpopulations still require research, there is a large body of literature that demonstrates the increased vulnerability to extreme heat of a number of groups, and therefore there is **very high confidence** that the listed populations of concern are at greater risk of temperature-related death and illness.

DOCUMENTING UNCERTAINTY

This assessment relies on two metrics to communicate the degree of certainty in Key Findings. See Appendix 4: Documenting Uncertainty for more on assessments of likelihood and confidence.

Confidence Level	
Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood	
Very Likely	≥ 9 in 10
Likely	≥ 2 in 3
As Likely As Not	≈ 1 in 2
Unlikely	≤ 1 in 3
Very Unlikely	≤ 1 in 10

PHOTO CREDITS

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